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Ventilation of ordinary face masks

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ABSTRACT

Wearing of face masks has been identified as an essential means of reducing COVID-19 infection during the pandemic. However, air leakage into ordinary face masks decreases the protection they provide. Wearing a mask also causes both CO_2 and humidity to accumulate inside, imposing breathing difficulty and discomfort. To remedy the above problems, this investigation proposed to ventilate ordinary masks by supplying additional HEPA filtered air. The N95, surgical, and cotton masks available on the market, were modified into ventilated masks. The air inside the masks was extracted for measurement of the $PM_{2.5}$, CO_2, and water vapor concentrations. The protection provided by the masks was evaluated in terms of their effectiveness in shielding wearers from ambient $PM_{2.5}$. Mask comfort was examined in terms of both CO_2 concentration and humidity ratio. In addition, a mathematical model was established to solve for the exchanged air flow rates via different routes. Subjective voting by 20 mask wearers was also conducted. Performance of the ventilated face masks were compared against the non-ventilated ones. It was found that the protection provided by the ordinary non-ventilated masks is much lower than that claimed for the filter materials alone due to significantly total inward leakage. The accumulated CO_2 and humidity inside masks resulted in discomfort and complaints. For contrast, the ventilated face masks not only enhanced protection by suppressing the inward leakage of ambient airborne particles, but also significantly improved comfort. The wearers preferred a filtered air flow rate ranging from 18 to 23 L/min.

1. Introduction

Face masks have been proven quite effective in lowering the rate of COVID-19 transmission during the pandemic [1]. Wearing a face mask not only decreases the shedding of COIVD-19 virus by infected individuals [2,3], but also minimizes respiratory exposure for susceptible individuals. Most confined spaces require the wearing of a face mask without an exhalation valve in order to reduce the possibility of virus release into the air. This may cause some breathing difficulty or discomfort, especially for sensitive people wearing N95-like high-efficiency masks.

The protection provided by face masks is subject to the total inward leakage (TIL). The TIL is defined as the concentration ratio of the aerosol inside the mask and the aerosol outside the mask. The aerosol inside the mask includes the aerosol penetrating the filter element and the aerosol leaking in through the gap between the mask and the face. The filtration efficiency of cotton mask material is lower than that of surgical mask material, which in turn is lower than that of N95 mask material. It has been claimed that the filtration efficiency of the N95 mask material can reach 99.5% [4]. Higher filtration efficiency corresponds to greater resistance to the permeation of air, and even an N95 mask with an ideal seal may not completely prevent penetration of aerosols [5].

The leakage of face masks is closely related to the mask type and shape [6,7]. A recent study [8] tested five types of face masks and revealed inward and outward leakage for all types except the N95 mask. The TIL of pleated-type masks was found to range from 48.5% to 70.8%, which was much higher than range for cup-type masks, from 0.3% to 5.6% [9]. The TIL was reduced from 32.1% to 10.5% by correct wearing of masks and improved fitting of the mask to the face [10]. However, face masks are a standardized product and cannot adapt to all face shapes.

Comfort is a key factor in the acceptability of face masks and the wearing rate by the general public. Wearing a mask may produce an uncomfortable local heat sensation, especially at a hot ambient temperature [11]. Furthermore, exhaled air may remain between the mask and the face [12], which constitutes dead space. Freely expired air is

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typically made up of 15.3% oxygen, 4.2% carbon dioxide, 6.2% water vapor, and 74.3% nitrogen [13]. The temperature of the expired air varies with the climate conditions and may also be different between nasally exhaled air and orally exhaled air [14]. At an ambient temperature of 23 °C, the freely expired air temperature is approximately 34 °C, which is nearly independent of the relative humidity. At −5 °C with 50% RH, the nasally exhaled air temperature is close to 23.5 °C, while the orally exhaled air temperature is 29 °C [14]. Face masks help to insulate the mouth and nose from the impact of the surrounding air temperature. Meanwhile, the CO_2 concentration inside masks has been measured at up to 4.45% [15], which is higher than the CO_2 concentration in freely expired air. The increased CO_2 concentration in the inhaled air during mask wearing is accompanied by decreased O_2 concentration. The O_2 debt may result in headache and increased sick days [16]. If the inhaled CO_2 concentration is between 7% and 7.5%, severe dyspnea, headache, dizziness, perspiration and even short-time memory loss may occur [17]. Wearing face masks inappropriately also increases breathing resistance, which may lead to respiratory fatigue, physical impairment, and transition to anaerobic metabolism [15].

Meanwhile, ventilated face masks may substantially increase the inhaled oxygen content, displace CO_2 and water vapor, and improve thermal sensation. Noninvasive positive pressure ventilation or oxygen supply through a helmet or face mask has been widely provided to patients with respiratory failure in hospitals [18,19]. A face mask connected to a portable air purifier by a soft tube was found to improve the thermal sensation in manikin tests [11] and in subjective evaluation [20,21], when subjects were stationary at a hot ambient temperature above 32 °C [11,20] or exercising at a comfortable ambient temperature of 18–20 °C [21]. When the air-supply rate to the face masks of subjects was reduced from 109.8 L/min to 0, their exercise times on a treadmill were found to decrease by 20% [21]. In a hot ambient environment, even an air-supply flow rate as low as 45 L/min could significantly decrease thermal stress and improve facial thermal comfort [20].

The above review revealed that face masks provide effective protection during a pandemic. The dead space in unventilated face masks may cause an elevated concentration of CO_2 and reduced concentration of O_2 for inhalation, in addition to discomfort, especially when masks are worn for long periods at a hot ambient temperature. Ventilated face masks seem a viable solution to the above dilemma. This investigation carried out measurements, modeling, and subjective evaluation of ventilated masks that were modified from three market-available types of face masks. Appropriate ventilation rates that were sufficient to dispose of exhaled CO_2 without causing discomfort were identified.

2. Methods

2.1. Ventilated face masks and experimental test

Three types of face mask available on the market were modified into ventilated masks, as shown in Fig. 1. These mask types included an N95 mask, a surgical mask, and a cotton mask. Each mask was connected to a soft silicone tube with a diameter of 0.015 m and a length of 0.65 m for ventilated air supply. The air-supply tube was very soft and light with a mass of 50 g/m. In addition to the air-supply tube, Fig. 1 shows the sampling port used to connect each type of mask with a sampling tube for particle and CO_2 concentration measurements, similar to the method in literature [6]. Both the air-supply tube and air sampling tube were securely connected to the mask without clearance for air leakage.

An adult wearing one of the ventilated masks was seated in a transparent chamber, as shown in Fig. 2 and Fig. A1 in the appendix, for performance tests, as similar to Ref. [22]. The chamber was mechanically ventilated at a volumetric flow rate of 15 L/s. During the experimental tests, the temperature of the room accommodating the chamber was controlled within the range of 23–27 °C with a relative humidity of 30%–50%. The face mask was provided with HEPA (high efficiency particulate air)-filtered air. The experimental setting somewhat resembled the scenario of a passenger seated in a commercial aircraft cabin and wearing a face mask with clean air supplied from an overhead gasper.

The filtered air flow rate was adjusted by changing the fan speed. During the test, the following filtered air flow rates into the face mask were used: 0, 12.42, 15.12, 18.12, 22.68, 27.06, 32.22 and 38.64 L/min. Some of the air inside the face mask was drawn by the sampling tube to a particle mass concentration monitor, then to a container with a temperature and humidity monitor, and finally to a CO_2 concentration monitor. Because the flow rate of the particle monitor (3.0 L/min) was much greater than that of the CO_2 monitor (a maximum of 1.8 L/min), only a small portion of the exhaust air from the particle monitor was delivered to the CO_2 monitor for measurement. This ensured that there was no apparent interference among the various test instruments.

During the test, no particle source was purposely released. The particle mass concentration inside the face mask was used to evaluate the performance of the mask in shielding the wearer from the $PM_{2.5}$ in the background air. The atmospheric $PM_{2.5}$ concentrations varied with the outdoor air pollution. Hence, the $PM_{2.5}$ concentrations inside the chamber before and after each test were monitored as the background $PM_{2.5}$ concentrations. Human exhaled air is humid; therefore, to prevent water condensation inside the sampling tube, the tube was wrapped with electrical film for heating to 40 °C. The particle monitor was also heated to ensure that the exhaust air temperature from the particle monitor exceeded 35 °C.

An adult male wearing the ventilated mask was sitting quietly and breathing normally through only the nose. The subject was in good health with a weight of 62 kg and a height of 1.7 m. The test was conducted from Nov. 2020 to Jan. 2021.

2.2. Mathematical modeling

Mathematical models were established to analyze the exchange of air, CO_2, $PM_{2.5}$, and water vapor inside the face mask. Available models

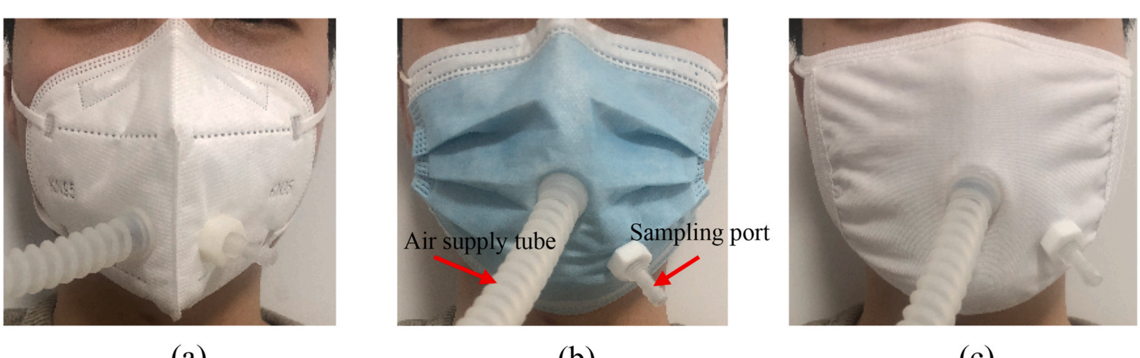

Fig. 1. Three ventilated face masks with individual HEPA filtered air supply for measurement tests: (a) N95 mask, (b) surgical mask, (c) cotton mask.

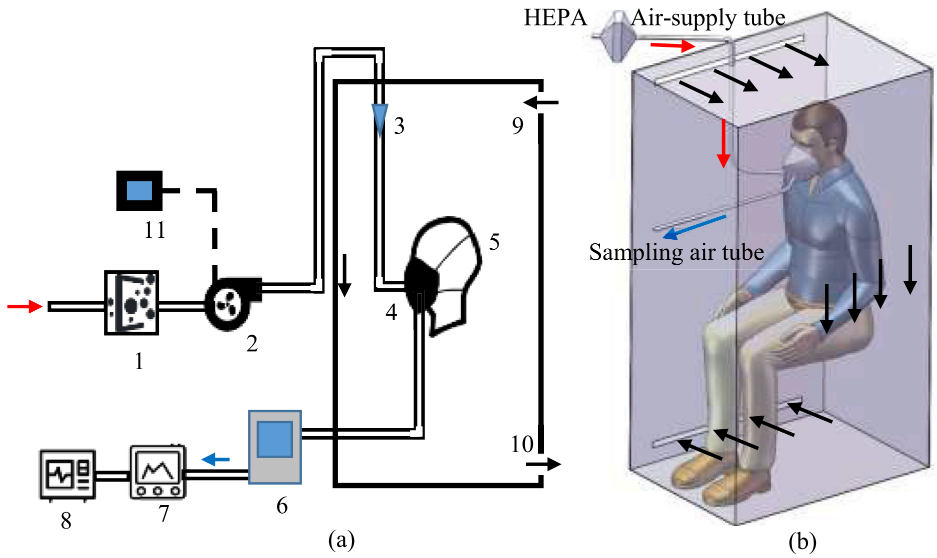

Fig. 2. Experimental test scheme: (a) schematic of principles, 1-HEPA filter, 2-fan, 3-air-supply tube, 4-face mask, 5-test subject, 6-particle monitor, 7-temperature and relative humidity monitor, 8-CO_2 concentration monitor, 9-background air supply, 10-background air exhaust, 11-fan speed controller; (b) 3D diagram.

on face mask are very limited [12]. The applied basic law in this investigation was conservation of mass for the steady state. An ordinary face mask without modification and the proposed ventilated face mask, as shown in Fig. 3, were modeled.

2.2.1. Ordinary face mask without modification for additional ventilation

In contrast with the typical wearing of face masks in daily life, air inside the face mask was extracted constantly for measurement of the $PM_{2.5}$ and CO_2 concentrations and humidity ratios, as shown in Fig. 3(a). The following assumptions were adopted for modeling:

1) Steady state process,
2) Co-existence of inhalation and exhalation at a constant rate,
3) Bidirectional leakage through the gap,
4) Bidirectional gas permeation through the filter material,
5) Well-mixed condition inside the face mask,
6) Constant humidity ratio of exhaled air,
7) No water vapor condensation or storage of vapor in the filter material,
8) Constant chamber air conditions, and
9) Neglect of variation in gas density with air temperature.

Based on the above assumptions and with reference to Fig. 3(a), the following conservation equations were established.

(1) Flow rate

The mass flow rate conservation was simplified as the volumetric rate balance and expressed as:

$$Q_{\mathrm{L,in}} + Q_{\mathrm{F,in}} + Q_{\mathrm{EX}} = \left(Q_{\mathrm{L,out}} + Q_{\mathrm{F,out}}\right) + Q_{\mathrm{Sa}} + Q_{\mathrm{IN}} \tag{1}$$

where $Q_{\mathrm{L,in}}$ is the leak-in flow rate into the mask, $Q_{\mathrm{F,in}}$ is the filter-in flow rate, Q_{EX} is the exhaled flow rate which was assumed to be 6 L/min [13] in this investigation, $Q_{\mathrm{L,out}}$ is the leak-out flow rate out of the mask, $Q_{\mathrm{F,out}}$ is the filter-out flow rate, Q_{Sa} is the sampling air flow rate at 3 L/min, and Q_{IN} is the human inhaled flow rate which was equal to 6 L/min. During the solution process, $(Q_{\mathrm{L,out}} + Q_{\mathrm{F,out}})$ was cast as a single term, so that the leak-out and filter-out air were not differentiated in this

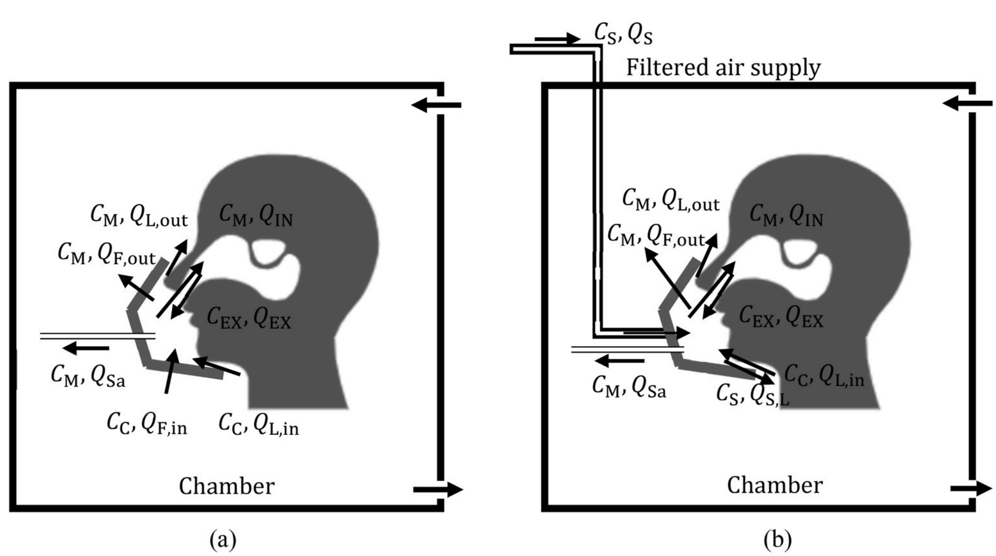

Fig. 3. Schematics of air flow and pollutant exchange: (a) face mask without ventilation during test, (b) ventilated face mask during test.

investigation.

(2) CO_2 concentration

Each term in Eq. (1) contributed to the CO_2 concentration balance. The CO_2 concentration equation could thus be written as:

$$Q_{L,in}\cdot C_{C,CO2} + Q_{F,in}\cdot C_{C,CO2} + Q_{EX}\cdot C_{EX,CO2} = \left(Q_{L,out} + Q_{F,out}\right)\cdot C_{M,CO2} + Q_{Sa}\cdot C_{M,CO2} + Q_{IN}\cdot C_{M,CO2} \tag{2}$$

where $C_{C,CO2}$ is the CO_2 concentration in the chamber air, which was measured at approximately 550 ppm; $C_{EX,CO2}$ is the exhaled CO_2 concentration and was assumed to be 42000 ppm; and $C_{M,CO2}$ is the well-mixed CO_2 concentration in the mask.

(3) $PM_{2.5}$ concentration

Following a similar process to that for the CO_2 concentration equation, the $PM_{2.5}$ concentration was established. In this case, however, both the filter and the human respiratory system could remove $PM_{2.5}$. The governing equation of $PM_{2.5}$ concentrations was thus written as:

$$Q_{L,in}\cdot C_{C,PM2.5} + Q_{F,in}\cdot(1-\eta_F)\cdot C_{C,PM2.5} + Q_{EX}\cdot(1-\eta_R)\cdot C_{M,PM2.5} = \left(Q_{L,out} + Q_{F,out}\right)\cdot C_{M,PM2.5} + Q_{Sa}\cdot C_{M,PM2.5} + Q_{IN}\cdot C_{M,PM2.5} \tag{3}$$

where $C_{C,PM2.5}$ is the background $PM_{2.5}$ concentration in the chamber air, $\mu g/m^3$; $C_{M,PM2.5}$ is the $PM_{2.5}$ concentration inside the mask, $\mu g/m^3$; η_F is the filtration efficiency of the filter, which according to our measurements was equal to 99% for the N95 mask, 85% for the surgical mask, and 10% for the cotton mask; and η_R was the percentage of $PM_{2.5}$ deposited in the respiratory system, which was assumed to be 85% [23] in this investigation.

(4) Humidity ratio

Because no condensation of water vapor or storage of vapor inside the filter material was considered, the governing equation of humidity was also similar to that of CO_2, and was expressed as:

$$Q_{L,in}\cdot\omega_C\cdot\rho_C + Q_{F,in}\cdot\omega_C\cdot\rho_C + Q_{EX}\cdot\omega_{EX}\cdot\rho_{EX} = \left(Q_{L,out} + Q_{F,out}\right)\cdot\omega_M\cdot\rho_M + Q_{Sa}\cdot\omega_M\cdot\rho_M + Q_{IN}\cdot\omega_M\cdot\rho_M \tag{4}$$

where ω_C is the humidity ratio of the chamber air, which was approximately 7.88 g/kg, corresponding to a dry bulb temperature of 25 °C and a relative humidity of 40%; ω_{EX} is the humidity ratio of the exhaled air and was assumed to be 31.56 g/kg; ω_M is the humidity ratio inside the mask; and ρ is density, which was treated as a constant in this investigation and thus could be cancelled out.

2.2.2. *Ventilated face mask with additional HEPA filtered air supply*

For the ventilated face mask, additional filtered air was supplied into the mask as shown in Fig. 3(b). Because the ventilation rate into the mask was greater than the adult subject's inhalation rate at rest, some of the filtered air leaked out without participating in the dilution. Hence, the air that leaked out of the mask could be divided into two parts: one portion that did not contribute to dilution of the air inside the mask, and another portion that fully diluted the air inside the mask. Due to resistance through the filter, the filter-in flow was assumed to be zero when filtered air was provided to the mask. However, the leak-in flow through the gap was considered. More details of the assumptions could be found in the appendix. The governing equations of flow rate, CO_2 and $PM_{2.5}$ concentrations, and humidity ratio were established as follows.

(1) Flow rate

$$Q_S + Q_{L,in} + Q_{EX} = Q_{S,L} + \left(Q_{L,out} + Q_{F,out}\right) + Q_{Sa} + Q_{IN} \tag{5}$$

where Q_S is the HEPA filtered supply air rate into the face mask, $Q_{S,L}$ is the leak-out of the filtered supply air without diluting the gas inside the mask, and again $\left(Q_{L,out} + Q_{F,out}\right)$ is cast into a single term for solution.

(2) CO_2 concentration

The governing equation for CO_2 concentration was:

$$Q_S\cdot C_{S,CO2} + Q_{L,in}\cdot C_{C,CO2} + Q_{EX}\cdot C_{EX,CO2} = Q_{S,L}\cdot C_{S,CO2} + \left(Q_{L,out} + Q_{F,out}\right)\cdot C_{M,CO2} + Q_{Sa}\cdot C_{M,CO2} + Q_{IN}\cdot C_{M,CO2} \tag{6}$$

(3) $PM_{2.5}$ concentration

The governing equation for $PM_{2.5}$ concentration was:

$$Q_S\cdot C_{S,PM2.5} + Q_{L,in}\cdot C_{C,PM2.5} + Q_{EX}\cdot(1-\eta_R)\cdot C_{M,PM2.5} = Q_{S,L}\cdot C_{S,PM2.5} + \left(Q_{L,out} + Q_{F,out}\right)\cdot C_{M,PM2.5} + Q_{Sa}\cdot C_{M,PM2.5} + Q_{IN}\cdot C_{M,PM2.5} \tag{7}$$

(4) Humidity ratio

The governing equation for water vapor was:

$$Q_S\cdot\omega_S\cdot\rho_S + Q_{L,in}\cdot\omega_C\cdot\rho_C + Q_{EX}\cdot\omega_{EX}\cdot\rho_{EX} = Q_{S,L}\cdot\omega_S\cdot\rho_S + \left(Q_{L,out} + Q_{F,out}\right)\cdot\omega_M\cdot\rho_M + Q_{Sa}\cdot\omega_M\cdot\rho_M + Q_{IN}\cdot\omega_M\cdot\rho_M \tag{8}$$

2.3. *Subjective evaluation*

A total of 20 adult engineering students in university were recruited for a questionnaire survey of their subjective feelings about face masks. Table 1 provides some basic information about the volunteers. They were equally divided between male and female and were in good health. Before completing the survey, each volunteer was asked to sit quietly in the laboratory for 10 min to allow stabilization of the metabolic rate. During the stabilization period, the test subjects were trained to wear the ventilated face mask. The survey questions were also explained to ensure that each question was fully understood. Next, each volunteer donned one of the face masks and stayed inside the chamber for at least 2 min. Subsequently, the survey questions were answered and collected. Each volunteer evaluated the three types of face mask, successively.

The subjective evaluation included: (1) the breathing difficulty presented by the mask, (2) the hot-humid feeling, (3) the weight-related discomfort of the mask, and (4) the air motion sensation inside the mask. The hot-humid feeling refers to the accumulated water vapor inside the mask that causes discomfort. The breathing difficulty, hot-humid feeling, and weight-related discomfort were evaluated on three levels: none, slight, and severe. The air movement sensation vote (AMSV) [24] was used to evaluate the air motion inside the mask, as shown in Fig. 4. The AMSV accounts for both strong and weak air movement that results in discomfort.

3. Results

In this section, the results of the $PM_{2.5}$ and CO_2 concentrations, the exchange airflow rates and humidity ratios, and the subjective

Table 1
Basic information about volunteers for subjective evaluation of the face masks.

Item	Gender	Background	Age/years	Weight/kg	Height/m
Value	10 males, 10 females	Engineering[a]	23.95 ± 1.28	62.05 ± 11.72	1.69 ± 0.08

[a] HVAC engineering: 10 males +8 females, Environmental engineering: 1 female, Biological engineering: 1 female.

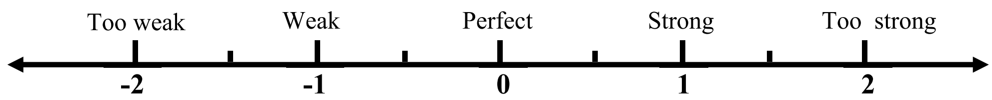

Fig. 4. Quantitative scale of air movement sensation vote (AMSV) used to evaluate the face masks.

evaluation of comfort for the three face mask types are presented.

3.1. $PM_{2.5}$ concentrations

Fig. 5 shows the measured $PM_{2.5}$ concentrations inside the N95 mask versus the supplied filtered air flow rate under background $PM_{2.5}$ concentrations of 9, 57, 114 and 238 μg/m^3, respectively. The background $PM_{2.5}$ concentrations were not controlled, but were nearly stable during a test, because the test did not take long. The $PM_{2.5}$ concentration in the filtered air supply was not completely zero but varied from zero to 10 μg/m^3, probably because of the clearance at the periphery of the HEPA filter or the particle generation by the fan. The data of the zero filtrated flow rate designate the original ordinary face masks without being modified. The corresponding results were highlighted in a different color to compare with those of the ventilated face masks.

At a background concentration of 9 μg/m^3, as shown in Fig. 5(a), the $PM_{2.5}$ concentrations inside the mask were zero. Without the filtered air supply, i.e., for the non-modified face mask, the measured concentration was slightly above zero. At higher $PM_{2.5}$ background concentrations, as shown in Fig. 5(b)–(d), the $PM_{2.5}$ concentrations decreased with the filtered air rate. At a rate of 22.68 L/min, the $PM_{2.5}$ concentrations in the mask approached the minimum. The $PM_{2.5}$ concentrations inside the mask did not further decrease with an increase in the filtered air rate. The minimum $PM_{2.5}$ concentration inside the mask was below 10 μg/m^3, which was quite close to the $PM_{2.5}$ concentration in the filtered air supply. Although the general trend is described above, there were fluctuations in the trend, as shown in Fig. 5 (b) and (c). The fluctuations were due to randomness in particle sampling, the mixing condition in the mask, and the fit of the mask to the face in each measurement, which resulted in leakage.

Note that the $PM_{2.5}$ concentration inside the non-modified face masks, i.e., at a zero filtrated flow rate, could be relatively high. For

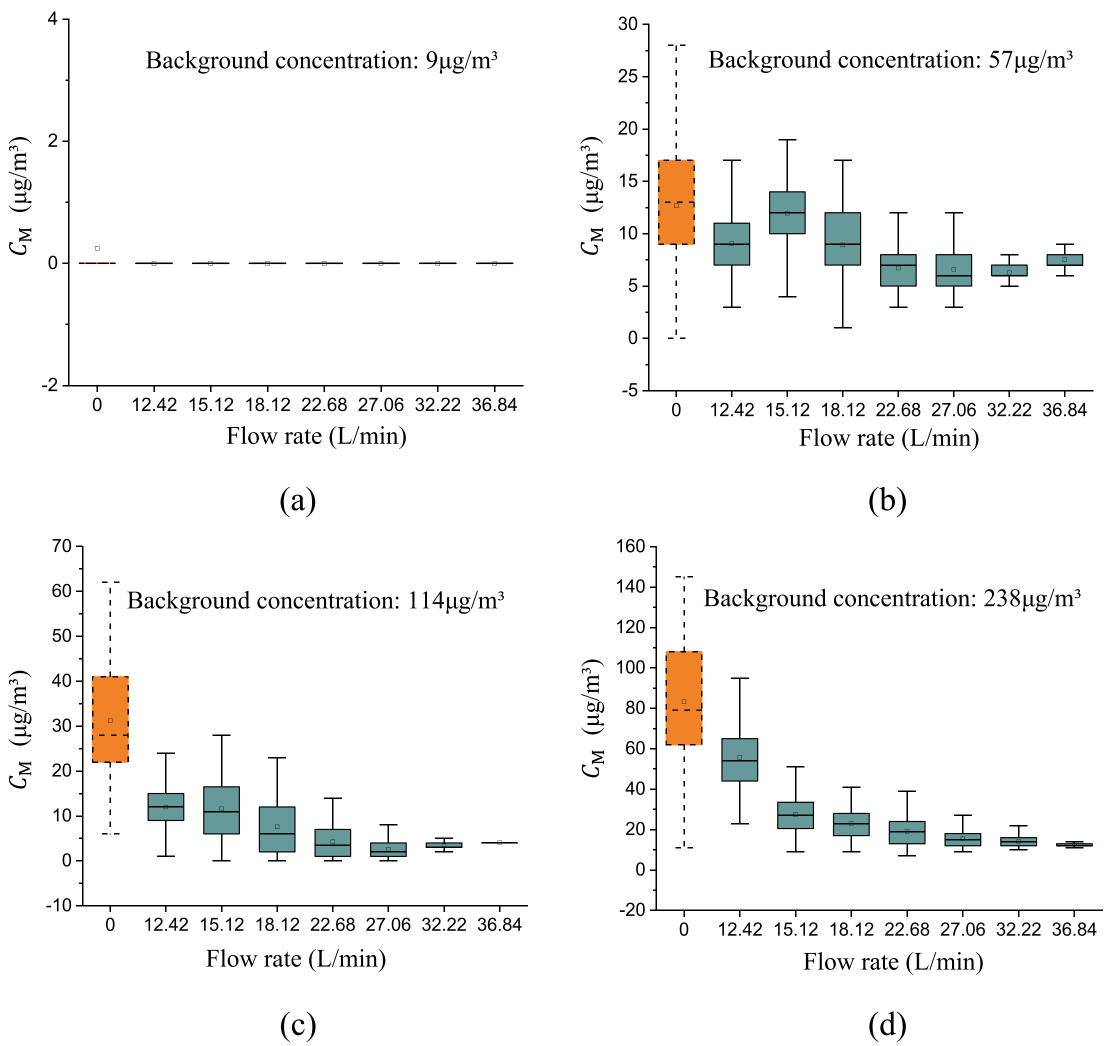

Fig. 5. Measured $PM_{2.5}$ concentrations inside the N95 mask versus the filtered air-supply rate into the mask under different background $PM_{2.5}$ concentrations, where each boxplot represents the minimum, 25th percentile, 50th percentile, mean (square symbol), 75th percentile, and maximum concentration, and the dashed lines and the boxes in orange designate the original non-modified face mask. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

example, the $PM_{2.5}$ concentration inside the face mask at a background concentration of 238 μg/m^3 reached 80 μg/m^3. This indicates insufficient protection by the N95 mask under a high exposure concentration when lacking with additional filtered air supply. The measured $PM_{2.5}$ concentrations and the associated analysis for the surgical and cotton masks can be found in the appendix.

To further evaluate the performance of the masks and the HEPA filtered air supply, the effectiveness of the masks in reducing the $PM_{2.5}$ concentration was defined as:

$$\varepsilon_{PM2.5} = 1 - \frac{C_M}{C_B} \tag{9}$$

where $\varepsilon_{PM2.5}$ is the effectiveness in shielding the wearer from the ambient $PM_{2.5}$, C_M is the $PM_{2.5}$ concentration in the mask, and C_B is the background $PM_{2.5}$ concentration in the chamber.

Fig. 6 presents the effectiveness of the three mask types under different filtered air flow rates. Each face mask was measured under four different background $PM_{2.5}$ concentrations, and the effectiveness in Fig. 6 is the average value from four different background concentrations. In general, the effectiveness of the face mask together with the filtered air supply increased with the filtered air flow rate. The average effectiveness approached the maximum when the filtered air flow rate exceeded 22.68 L/min. Further increasing the filtered air flow rate to greater than 22.68 L/min resulted in little increase in the effectiveness. The effectiveness of the N95 mask ranged from 62.2% to 100%, for the surgical mask from 41.9% to 93.3%, and for the cotton mask from 35.4% to 87.8%. Fig. 6 clearly compares the protective ability of the different mask types. The effectiveness of the face masks in reality is much lower than the claimed effectiveness of the filter materials alone.

3.2. CO_2 concentrations

The dead space [12] in the mask locks in the exhaled air, which results in high concentrations of CO_2 and water vapor inside the mask. The dead space is one of the most critical factors in breathing difficulty and discomfort.

Fig. 7 shows the measured CO_2 concentrations inside the masks versus the filtered air flow rate. The CO_2 concentrations inside the masks were much higher than the background CO_2 concentration of 550 ppm. This indicates that dead space was formed in each type of mask. Generally, the CO_2 concentration in the mask decreased with the filtered air flow rate. Even under the maximum flow rate, the CO_2 concentration inside the mask was much greater than that in the background air. However, the rate of decrease of the CO_2 concentration with the increase in filtered air flow rate was much reduced when the filtered air flow rate exceeded 27.06 L/min. Note that, without the filtered air supply for the unmodified face masks, the CO_2 concentration inside the mask was close to 2.17% regardless of the mask type. The measured CO_2 concentration

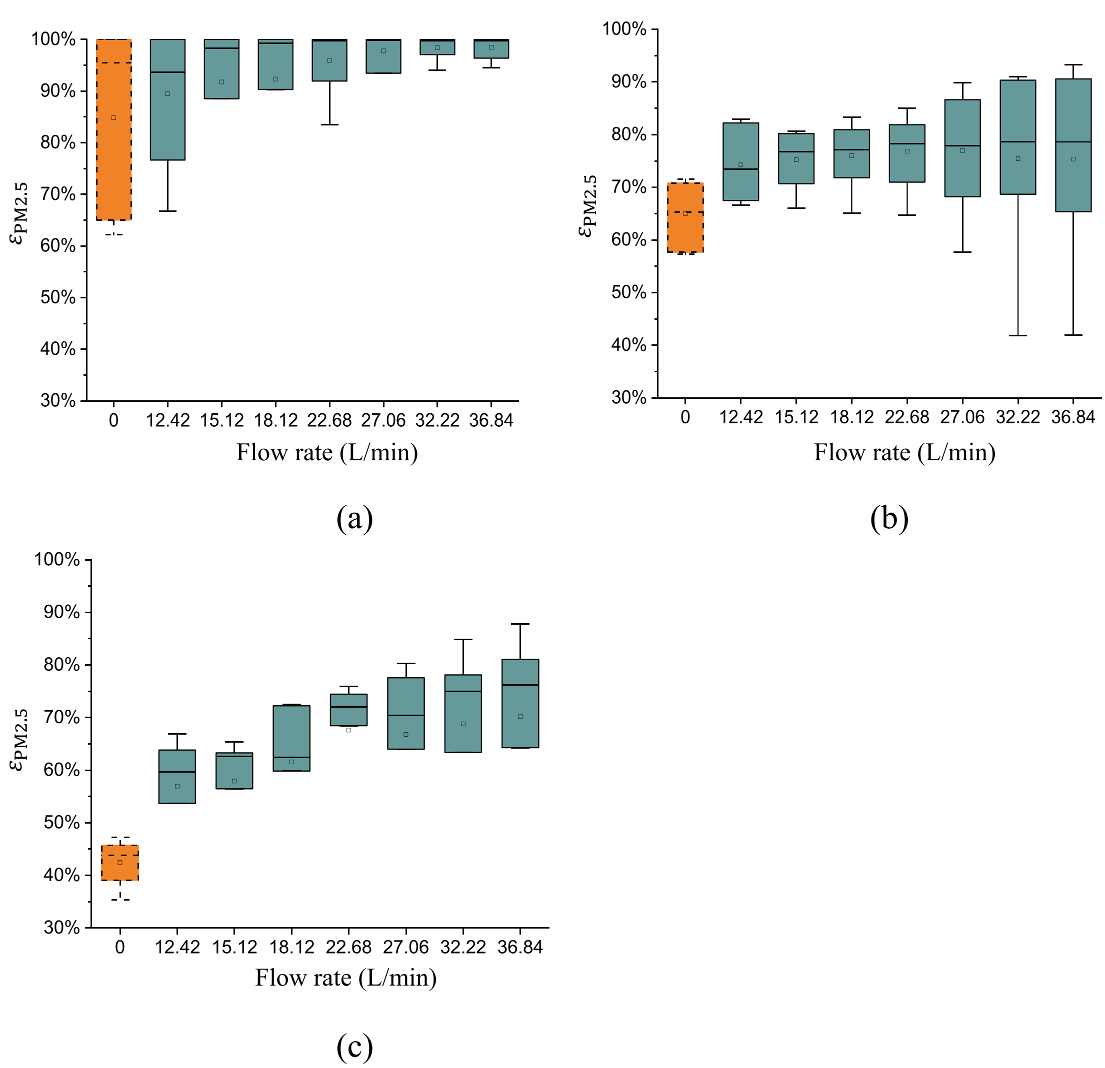

Fig. 6. Effectiveness of the face masks under different filtered air flow rates in shielding from ambient background $PM_{2.5}$ for: (a) the N95 mask, (b) the surgical mask; (c) the cotton mask.

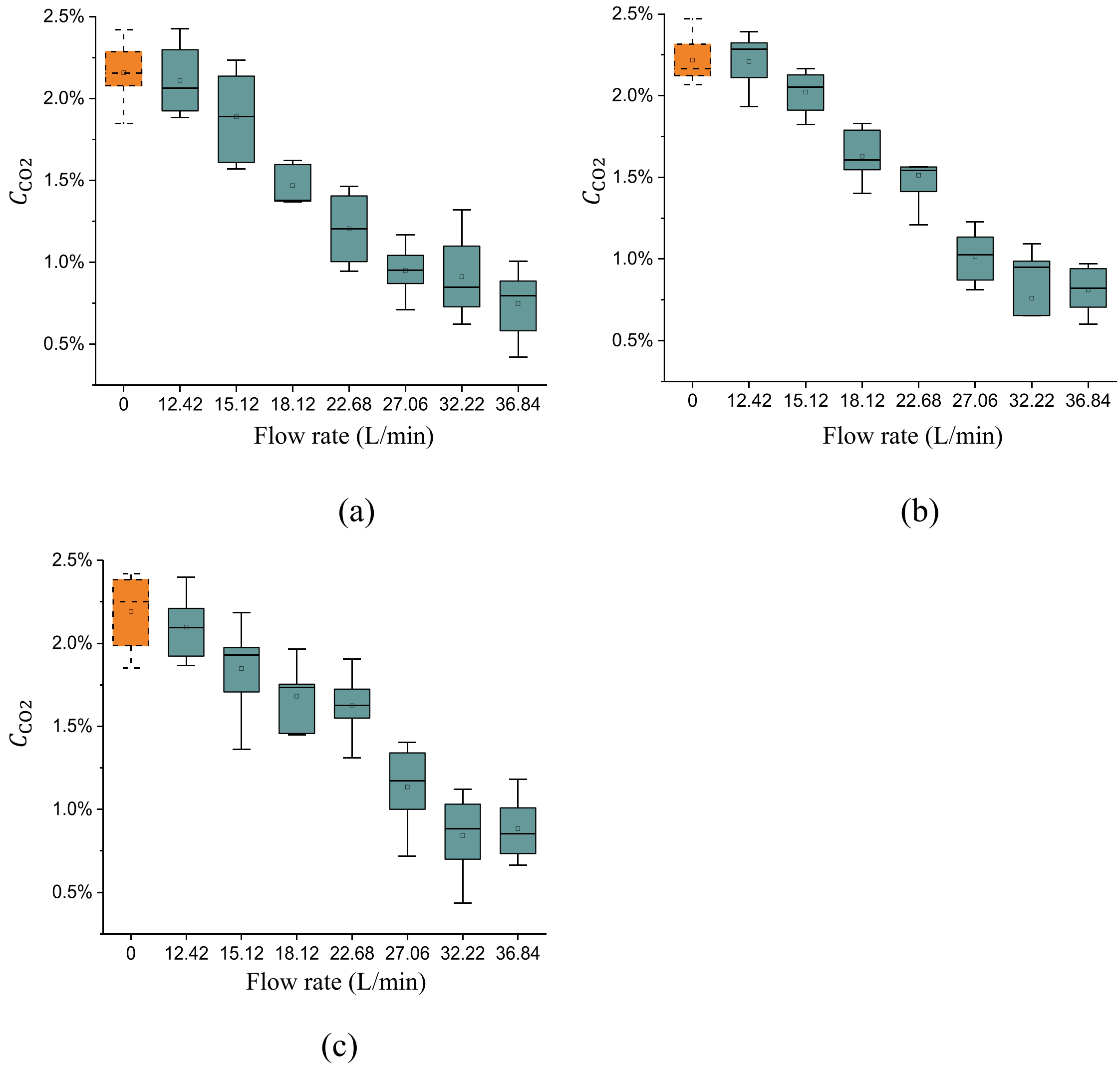

Fig. 7. Measured CO_2 concentrations inside face masks versus the filtered air flow rate for: (a) the N95 mask; (b) the surgical mask; (c) the cotton mask.

was similar to the reported 2.49% in an N95 mask under a respiratory flow rate of 11.9 L/min [15].

Similar to the effectiveness evaluated by the $PM_{2.5}$ concentration, the effectiveness in shielding from exhaled CO_2 was defined as:

$$\varepsilon_{CO2} = 1 - \frac{C_{M,V}}{C_{M,0}} \tag{10}$$

where ε_{CO2} is the effectiveness in shielding from the exhaled CO_2 inside the face mask, $C_{M,V}$ is the CO_2 concentration in the mask with the filtered air supply, and $C_{M,0}$ is the CO_2 concentration in the mask when the filtered air flow rate is zero.

Fig. 8 shows the effectiveness of different face masks in shielding from the exhaled CO_2. The effectiveness generally increased with the filtered air flow rate. At a flow rate of 22.68 L/min, the effectiveness was approximately 45.1% for the N95 mask, 37.1% for the surgical mask, and 43.6% for the cotton mask. When the filtered air flow rate exceeded 27.06 L/min, there was a slower increase in the effectiveness with the flow rate. Even under the highest tested filtered air flow rate of 38.64 L/min, the maximum effectiveness was lower than 70%. This indicates that the outdoor air rate was not sufficient to affect the CO_2 concentration inside the mask.

3.3. Exchanged air flow rates

Based on the measured $PM_{2.5}$ and CO_2 concentrations in Sections 3.1 and 3.2, Eqs. (1)–(3) were solved for the unmodified masks without provision of filtered air. Likewise, Eqs. (5)–(7) were solved for the masks with filtered air supply. The $PM_{2.5}$ concentrations used here were based on the case with the highest background $PM_{2.5}$ concentration for each mask type, i.e., from Fig. 5(d) for the N95 mask, Fig. A2(d) for the surgical mask, and Fig. A3(d) for the cotton mask.

As shown in Table 2, the solved inward leakage air flow increased from the N95 mask to the surgical mask and then to the cotton mask, sequentially, in accordance with the mask-fit ranking. The N95 mask exhibited the best fit and thus corresponded to the smallest inward leakage air flow. The $PM_{2.5}$ in the masks was mainly due to the leak-in flow. Because the filter of the cotton mask had a very low filtration efficiency of 10%, the ambient air entering the mask by inward leakage or through the filter did not greatly impact the $PM_{2.5}$ concentration inside the mask. The sum of $Q_{L,in}$ and $Q_{F,in}$ with the subtraction of $(Q_{L,out} + Q_{F,out})$ was the air flow rate extracted for measuring the $PM_{2.5}$ concentrations, which was close to 3.0 L/min.

Table 3 presents the solved air flow rates for the masks provided with additional filtered air. The first column lists the filtered air flow rates. Because these flow rates were greater than the typical respiratory flow rate for an adult sitting quietly. The flow rate through the filter of each

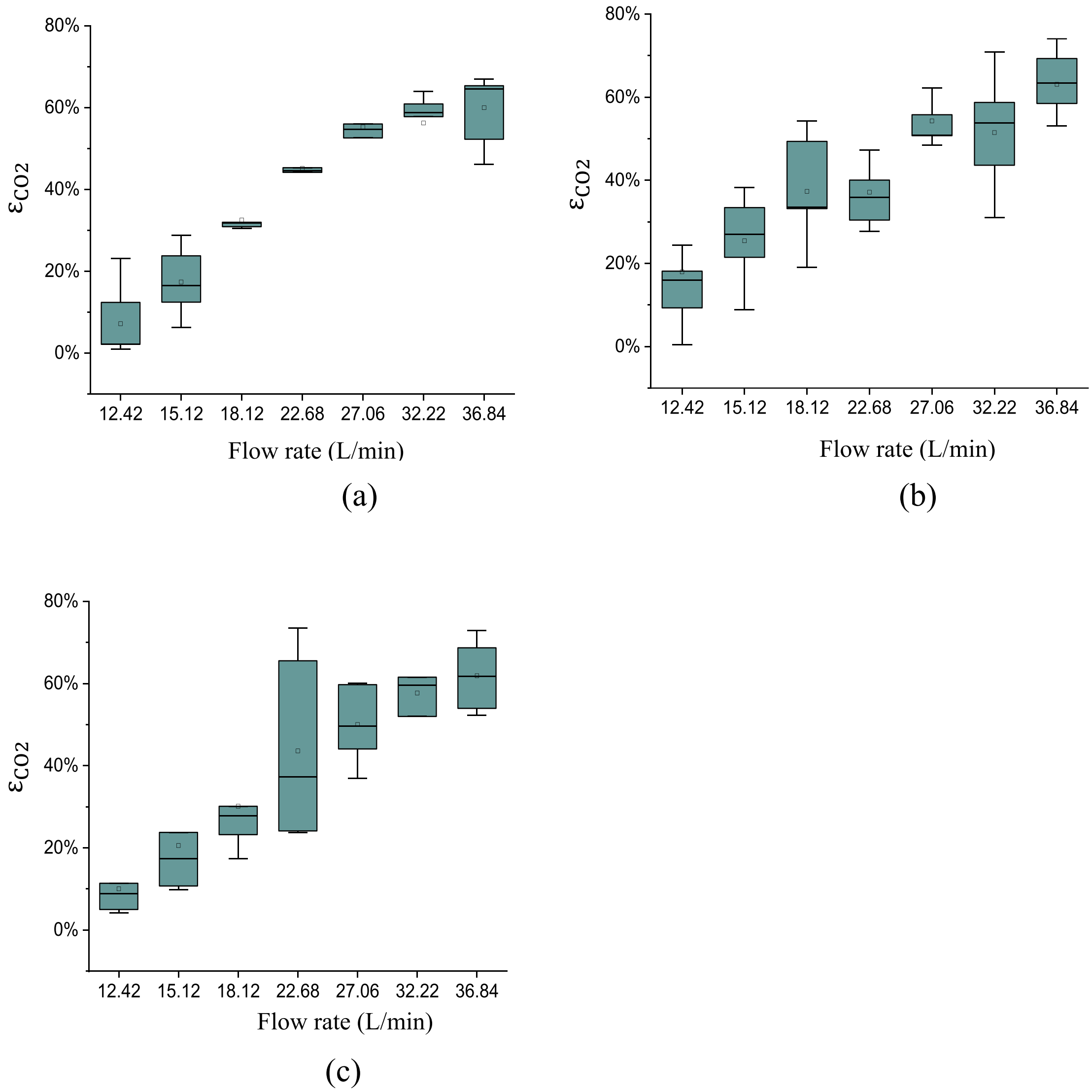

Fig. 8. Effectiveness of the face masks under different filtered air flow rates in shielding from the exhaled CO_2 for: (a) the N95 mask; (b) the surgical mask; (c) the cotton mask.

Table 2
Exchanged air flow rates for non-ventilated face masks.

Type	$Q_{L,in}$, L/min	$Q_{F,in}$, L/min	$(Q_{L,out} + Q_{F,out})$, L/min
N95 mask	3.77	1.97	2.75
Surgical mask	3.84	2.19	3.03
Cotton mask	5.53	0.07	2.60

mask was assumed to be zero, just as was assumed in Section 2.2.2. However, both the inward leakage, represented by $Q_{L,in}$, and the loss of the filtered air without participating in air mixing inside the mask, represented by $Q_{S,L}$, were possible. Only the amount of the filtered air supply equal to $(Q_S - Q_{S,L})$ participated in air mixing inside the mask. As the filtered air flow rate increased, the inward leakage rate decreased for the N95 and surgical masks. However, the trends in variation for the cotton mask were complicated, mainly due to fluctuations in the measured $PM_{2.5}$ concentrations. The inward leakage rate of the N95 mask was lower than that of the surgical mask, which in turn was lower

Table 3
Exchanged air flow rates for face masks provided with additional HEPA filtered air.

Q_S, L/min	$Q_{L,in}$, L/min			$Q_{S,L}$, L/min			$(Q_{L,out} + Q_{F,out})$, L/min		
	N95	Surgical	Cotton	N95	Surgical	Cotton	N95	Surgical	Cotton
12.42	2.47	4.01	4.87	8.84	7.76	10.81	3.05	5.67	3.48
15.12	1.24	3.83	5.05	8.36	8.72	12.61	5.00	7.24	4.56
18.12	1.20	3.14	4.96	8.01	7.81	13.44	8.31	10.45	6.64
22.68	1.10	2.88	5.02	8.21	12.13	15.23	12.57	10.43	9.47
27.06	0.90	2.30	4.40	7.96	8.29	16.17	17.00	18.07	12.28
32.22	0.78	2.06	3.84	10.74	14.78	16.13	19.27	16.50	16.93
36.84	0.68	1.57	3.32	13.68	10.34	15.22	20.84	25.07	21.94

than that of the cotton mask. The $(Q_{L,out} + Q_{F,out})$ generally increased with the filtered air flow rate. Note that the solved air flow rates were highly subject to the assumptions adopted and the quality of the measured $PM_{2.5}$ and CO_2 concentrations.

3.4. Humidity ratios

With the exchanged air flow rates from Section 3.3, Eq. (4) was solved for the humidity ratio inside the unmodified masks without filtered air supply. Similarly, Eq. (8) was solved for the ventilated masks with filtered air supply. Fig. 9 presents the solved humidity ratios versus the filtered air flow rate for the different mask types. Without the filtered air supply, the average humidity ratio inside the face mask was approximately 20 g/kg regardless of the mask type. Such a humidity ratio was much higher than the comfort value of 7.88 g/kg, which corresponds to a dry bulb temperature of 25 °C and a relative humidity of 40%. As the filtered air flow rate increased, the humidity ratio inside the mask decreased gradually. Taking the N95 mask as an example, a filtered air flow rate greater than 18.12 L/min could reduce the humidity ratio to 16.1 g/kg, which would greatly improve the wearer's comfort. The solved humidity ratios in the cotton mask fluctuated with the filtered air flow rate, mainly because of the random mixing caused by the large gap between the mask and face.

In Fig. 9(a)–(c), the measured humidity ratios were also plotted for comparison with the solved values. In general, the measured and modeled humidity ratios were more or less in agreement with each other. For the N95 mask, the modeling under-calculated the humidity ratios when the filtered air flow rate was less than 15.12 L/min, but over-calculated the humidity ratios when the filtrated air flow rate exceeded 18.12 L/min. For the surgical mask, the modeling over-calculated nearly all the humidity ratios, while it under-calculated nearly all the humidity ratios for the cotton mask. Nevertheless, the measured humidity ratios were highly dependent on the mixing condition inside the mask, whereas the modeling assumed perfect mixing.

Fig. 9(d) presents the predicted humidity ratio for a passenger on a commercial aircraft wearing the N95 mask and provided with filtered air from the overhead gasper. The gasper air was clean and had an assumed humidity ratio of 1.1 g/kg, corresponding to 20 °C and 6% RH under 0.8 atm. Although the air supplied by the overhead gasper was very dry, the humidity ratio inside the mask at a filtered air rate of 22.68 L/min was close to 11 g/kg, which approached the comfort line [25]. Hence, the proposed ventilated face mask would improve the comfort of wearers during flights.

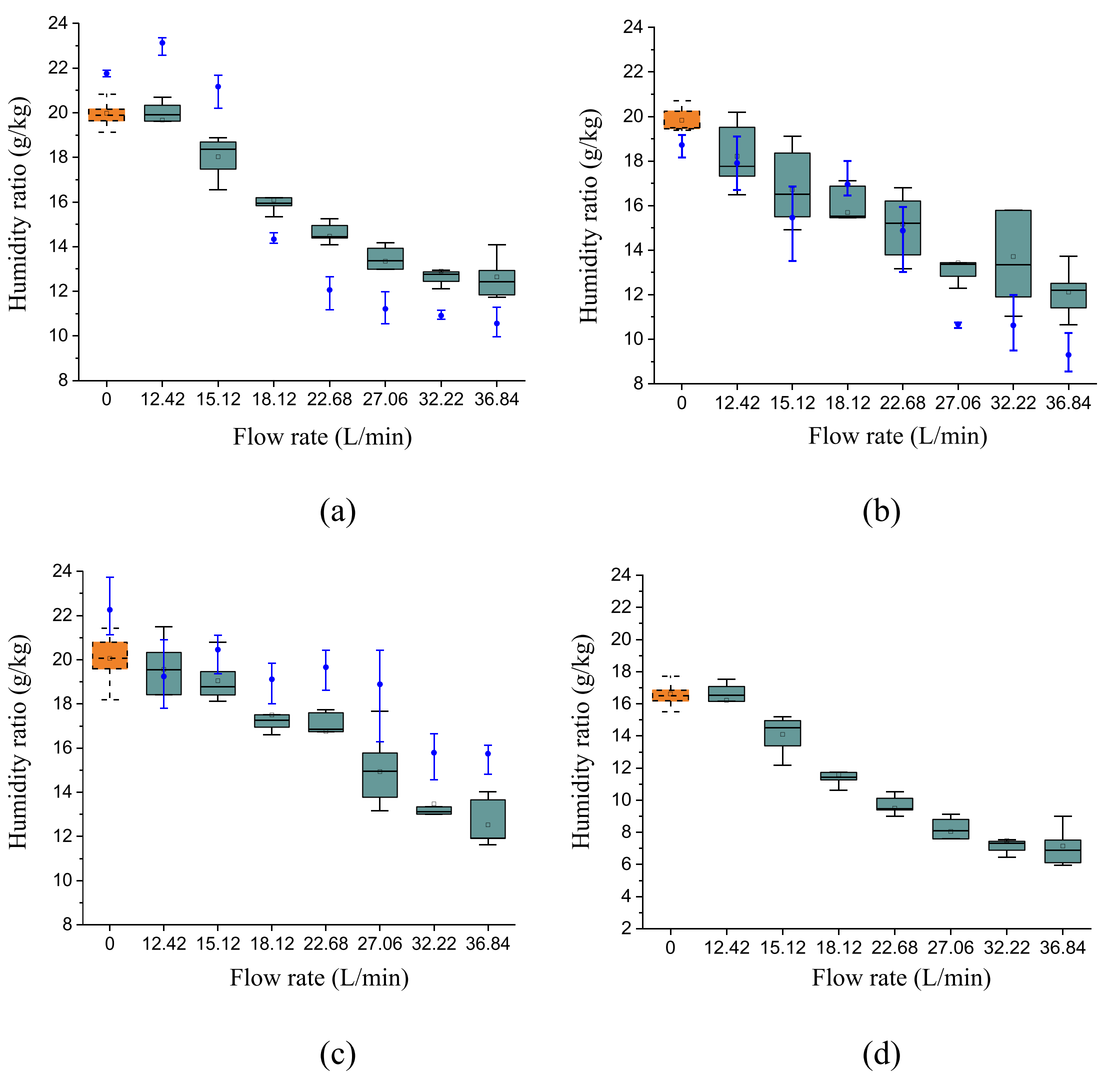

Fig. 9. Humidity ratios inside different face masks: (a) N95 mask, (b) surgical mask, (c) cotton mask, where in (a) to (c) the boxes represent measured values and the rest represent calculated values, and (d) predicted humidity ratio in the N95 mask when overhead gasper air is used to ventilate the mask during a flight.

3.5. Subjective evaluation

The subjective evaluation included three aspects: (1) breathing difficulty and hot-humid feeling, (2) acceptability of the filtered air flow rate, and (3) weight-related discomfort of the mask wearer. Table 4 presents the voting results for the breathing difficulty and hot-humid feeling. Without the filtered air supply, i.e., for the original unmodified masks, only 10% of the volunteers expressed no breathing difficulty when wearing the N95 mask. In contrast, more than half of the surgical and cotton mask wearers reported no difficulty in breathing. The breathing difficulty was negatively correlated with the filter's filtration efficiency and the fit of the mask to the face. Without the filtered air supply, more than 80% of N95 mask wearers, 75% of surgical mask wearers, and 65% of cotton mask wearers complained of hot-humid discomfort. The hot-humid complaint can be explained by the high humidity ratios shown in Fig. 9. The humidity ratio without the filtered air supply was approximately 20 g/kg, which was much higher than the ratio in a comfortable environment.

Table 4 also presents the voting results for ventilated masks provided with filtered air. For each volunteer, the voting was carried out at his/her preferred air flow rate. With the filtered air supply, none of the N95 mask wearers complained of breathing difficulty or hot-humid discomfort. Less than 20% of the surgical mask and cotton mask wearers reported breathing difficulty or hot-humid feeling. Thus, the filtered air supply was very effective in increasing the wearers' comfort.

Fig. 10(a) shows the percentage of volunteers who voted AMSV = 0 for the filtered air flow rates used in this study. According to Fig. 4, AMSV = 0 indicates that the given air flow rate is completely acceptable. More than 50% of the volunteers preferred the filtered air flow rates of 18.12 and 22.68 L/min regardless of the mask type. At these two flow rates, the surgical and cotton mask wearers voted a higher acceptability than the N95 mask wearers. The difference can be ascribed to a larger air-leakage gap for the surgical and cotton masks than for the N95 mask. When the filtered air flow rate exceeded 27.06 L/min, the acceptable percentage dropped below 40%. None of the volunteers found the filtered flow rate of 38.64 L/min to be acceptable, which implies that this rate was too high.

Fig. 10(b) presents the averaged vote scales according to Fig. 4. A negative value means that the filtered air flow was too weak, while a positive value indicates that it was too strong. The filtered air flow rate of 18.12 L/min caused slightly weak air motion for the N95 and cotton mask wearers, whereas it was completely acceptable for the surgical mask wearers. The flow rate of 22.68 L/min caused slightly strong air motion, with the AMSV less than 0.5. It was therefore concluded that a filtered air flow rate ranging from 18 to 23 L/min was most acceptable to the volunteers.

Table 5 provides the voting results for weight-related discomfort for each mask type. Ideally, ventilated face masks would be light enough so that the wearers do not complain about the weight. None of the mask types was free of weight-related complaints. For the N95 mask, 75% of wearers reported no weight-related discomfort. This may have been due to the more rigid structure of the cup-type N95 mask, which provided good support for the filtered air supply tube. Meanwhile, 60% of the surgical mask wearers complained of slight weight-related discomfort. For the cotton mask, 60% of wearers complained of slight weight-related discomfort, while 15% reported severe discomfort. Apparently, modification of the N95 mask into a ventilated mask was preferred over modification of the other mask types.

4. Discussion

This investigation used $PM_{2.5}$ concentrations to evaluate the protection provided by three different types of face masks. The $PM_{2.5}$ concentration inside the masks was greatly reduced from the exposure experienced without a mask. With the exception of the N95 mask provided with filtered air at a very low background $PM_{2.5}$ concentration, none of the masks in the tests were measured at zero $PM_{2.5}$ concentration. This indicates a certain total inward leakage of airborne particles. None of the face masks, even when provided with additional HEPA filtered air, can provide 100% protection. Wearers should be cautious in light of this potential protection failure.

In regard to ethical concerns, no purposeful release of $PM_{2.5}$ was performed. Consequently, the background $PM_{2.5}$ concentrations were not under control. The measurements were conducted under four different background $PM_{2.5}$ concentrations that varied with the outdoor air pollution. This variation resulted in measurement uncertainty. Furthermore, the particle monitor employed a laser numbering technique. Although the monitor was calibrated with the particle mass concentration, it did not measure mass concentration directly. In particular, a high relative humidity that caused vapor to condensate on ultra-fine particle nuclei might cause over-measurement of the particle mass concentration. Fortunately, the air extracted for particle concentration measurement had been heated above 35 °C.

Human-expired air contains high concentrations of CO_2 and water vapor. The huge difference in CO_2 concentration between the expired air and the ambient air made accurate measurement difficult. That is, the measured CO_2 concentration may have been dependent on the mixing status of the expired air with the inward leakage air, the air permeating the filter, and the filtered supply air. The dynamic respiratory process, which includes inhalation, pause, and exhalation, also impacted the mixing of the air in the mask. For evaluation of the humidity ratio, the air extracted from the mask was measured for air temperature and relative humidity. To prevent water vapor condensation, the extracted air tube and the particle monitor were heated. The heating generated a temperature difference with the surrounding air, which may have affected the accuracy of the extracted air temperature and relative humidity measurements.

Modeling of the air exchange in a face mask was very challenging, requiring numerous assumptions. The most critical assumption was the complete mixing of the air inside the mask. In our analysis, we treated the measured $PM_{2.5}$, CO_2, and water vapor concentrations as occurring under well-mixed conditions. As discussed above, the dynamic human breathing process and the momentum interaction may have resulted in non-well-mixed scenarios. The respiratory rate of 6 L/min used in this study was based on the simultaneous coexistence of steady exhalation and inhalation, i.e., neglecting the realistic sinusoidal wave and the pause. More elaborate modeling of the ventilated face mask and validation of the models with high-quality measurement data are needed in

Table 4
Voting results for breathing difficulty and hot-humid feeling.

Ventilation	Mask type	Breathing difficulty			Hot-humid feeling		
		None	Slight	Severe	None	Slight	Severe
No	N95 mask	10%	55%	35%	20%	60%	20%
	Surgical mask	55%	45%	0	25%	65%	10%
	Cotton mask	65%	15%	20%	35%	55%	10%
Yes	N95 mask	100%	0	0	100%	0	0
	Surgical mask	95%	5%	0	90%	10%	0
	Cotton mask	80%	20%	0	85%	15%	0

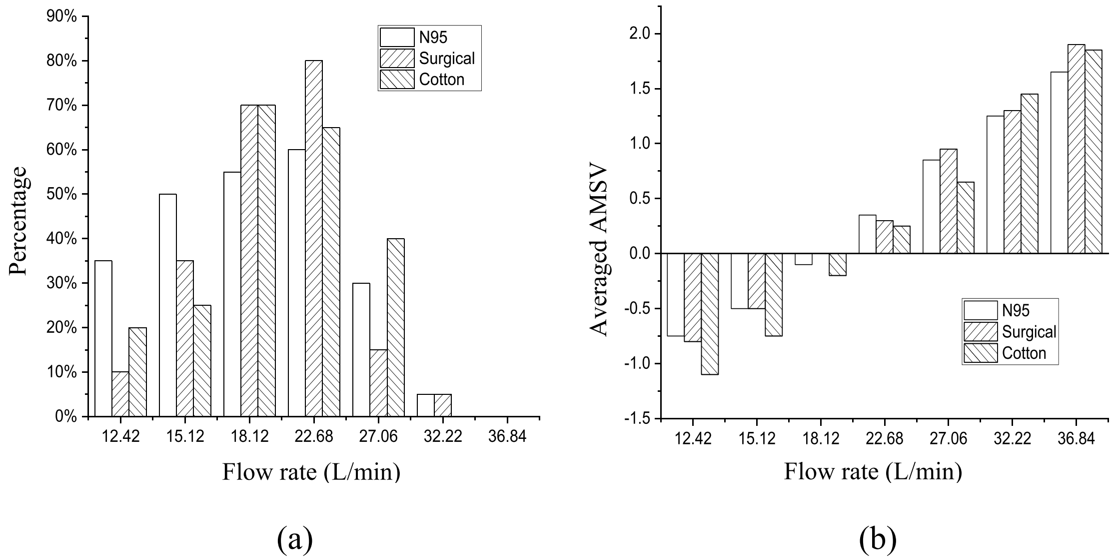

Fig. 10. Acceptability of different filtered air flow rates: (a) percentage of volunteers who voted AMSV = 0 for each flow rate; (b) averaged AMSV for each flow rate.

Table 5
Voting results for weight-related discomfort when the face masks were worn together with the filtered air supply tube.

Type	None	Slightly	Severely
N95 mask	75%	25%	0
Surgical mask	40%	60%	0
Cotton mask	25%	60%	15%

future studies.

Only 20 student volunteers in similar ages were recruited for the subjective evaluation. Most of them had a background in HVAC, which may have created some bias in their evaluation. The same environment may receive different feedback from the volunteers due to differences in understanding of comfort. The volunteers only represent a very small number of the general public and note that most general public lacks a professional knowledge of comfort. In addition, the careers, ages, races, habitats, and so on may impact the poll results. A more comprehensive subjective evaluation of the face masks could be achieved through consideration of volunteers with a greater diversity of backgrounds. In particular, some of the volunteers complained about the touch of the filtered air supply tube connector by their mouths when testing the surgical and cotton masks, and this annoyance may have contributed to their negative evaluation of these two mask types.

The ventilated face masks are quite promising in providing better protection during the pandemic. Such ventilated face masks could be considered for use on commercial aircraft, trains, and buses, where overhead filtered air supply is possible. The filtered air may also be provided by a portable self-powered HEPA unit in the wearer's pocket or wrapped around the arm.

5. Conclusions

This investigation proposed to ventilate face masks to enhance protection and comfort. Three types of masks, including N95, surgical, and cotton masks available on the market, were modified into ventilated face masks. The performance of the ventilated masks was evaluated by measurement, modeling, and subjective evaluation. Based on the results obtained in this study, the following conclusions can be drawn:

(1) Ordinary non-ventilated face masks were found to have significant total inward leakage. The protection provided by the masks is much lower than the that claimed for the filter materials alone. Both CO_2 and water vapor accumulate inside the mask, resulting in breathing difficulty and discomfort.
(2) The ventilated face masks with a filtered air supply not only enhance protection by suppressing the total inward leakage of ambient airborne particles, but also improve comfort by reducing the CO_2 concentration and humidity ratio inside the mask, regardless of the mask type. The higher the HEPA filtered air flow rate, the lower are the measured airborne particle, CO_2, and water vapor concentrations.
(3) A filtered air flow rate ranging from 18 to 23 L/min was most acceptable to the volunteers. The N95 mask with a rigid cup shape is the most appropriate for modification into the ventilated face mask. Because of the soft structure of the surgical and cotton masks, the filtered air supply tube attached to these masks may come into contact with the wearer's mouth and give rise to complaints.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

A.1. Supplemental methods

As shown in Fig. A. 1, the test chamber was equipped with ventilated face masks for both parametric measurements and subjective evaluation. The chamber was transparent, made of plexiglass. The dimensions of the chamber were 0.9 m × 0.64 m × 1.6 m. The chamber was mechanically ventilated inside an air-conditioned room. The room air was supplied into the chamber through a rectangular vent with dimensions of 0.69 m × 0.025 m in the side wall near the ceiling. The air exhaust with dimensions of 0.69 m × 0.025 m was located near the floor on the same side wall of the chamber.

Fig. A.1. A ventilated chamber equipped with a ventilated mask for study.

The particle monitor (type: 8533; TSI, USA) had a resolution of the greater value between 0.1% of the reading and 0.001 mg/m^3 in the measurement range of 0.001–150 mg/m^3. The flow rate of the particle monitor was 3.0 L/min with an accuracy of ±5%. The temperature and humidity sensor (type: HMT333; Vaisala, Finland) had a resolution of 0.1 °C and 0.1% RH, and an accuracy of ±0.2 °C and ±1% RH (0–90% RH) or ±1.7% RH (90–100% RH). The CO_2 monitor (type: 1412; Innova, Denmark) had a resolution of 1 ppb with a repeatability of 1%. The flow rate of the CO_2 monitor was 1.8 L/min when flushing the sampling tube and 0.3 L/min when measuring the concentration.

The following assumptions were adopted when modeling the ventilated face masks provided with the HEPA filtrated air:

1) Steady-state process,
2) Constant filtered air rate into the mask with constant $PM_{2.5}$ concentration,
3) A portion of the filtered air supply into the mask leaked out without contributing to dilution,
4) Bidirectional leakage through the gap,
5) No filter-in air passing through the mask's filter material,
6) Co-existence of inhalation and exhalation at a constant rate,
7) Well-mixed condition inside the face mask,
8) Constant humidity ratio of exhaled air,
9) No water vapor condensation or storage of vapor in the filter material,
10) Constant chamber air conditions, and
11) Negligible variation in gas density with air temperature.

A.2. Supplemental results

Fig. A.2 shows the $PM_{2.5}$ concentrations in the surgical mask versus the filtered air flow rate under background concentrations of 10, 65, 97 and 219 μg/m^3, respectively. In general, the $PM_{2.5}$ concentrations in the mask decreased with the filtered air rate, with the exception of the background concentration of 10 μg/m^3. This exception may have been due to variation in the gap between the mask and the face while the subject was breathing. Nevertheless, the $PM_{2.5}$ concentration in Fig. A2(a) was less than 5 μg/m^3, which was lower than the background concentration by at least 50%. As compared with Fig. 5 for the N95 mask, the $PM_{2.5}$ concentrations in the surgical mask were higher, implying poorer protection by the surgical mask than by the N95 mask. This difference was ascribed to worse fitting of the surgical mask than of the N95 mask. The filtration efficiency of the filter material of the surgical mask was also lower than that of the N95 mask.

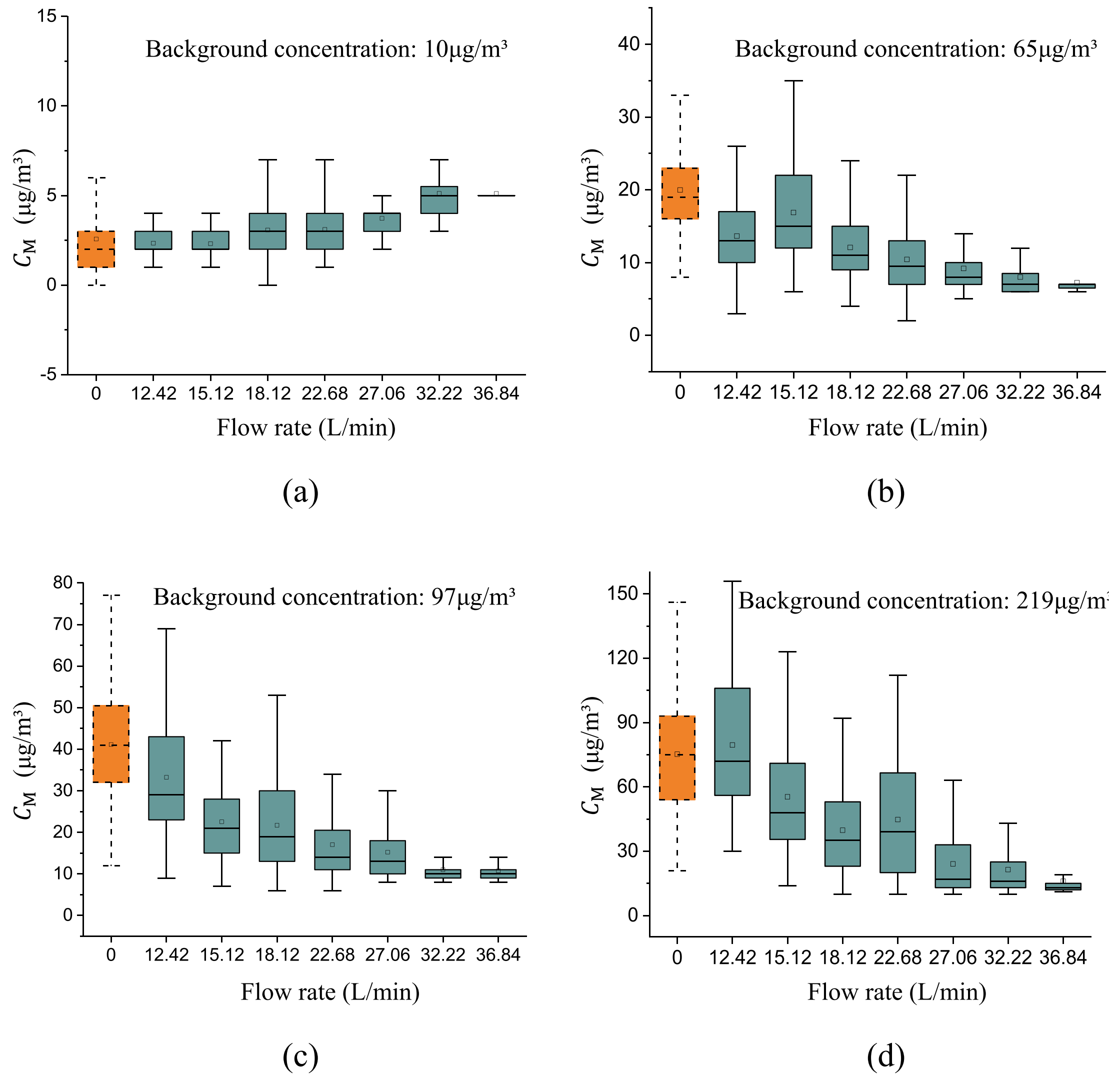

Fig. A.2. Measured $PM_{2.5}$ concentrations inside the surgical mask versus the filtered air-supply rate into the mask under different background $PM_{2.5}$ concentrations.

Fig. A.3 presents the measured $PM_{2.5}$ concentrations inside the cotton mask under different background concentrations. Similarly, the $PM_{2.5}$ concentrations in the cotton mask decreased with the filtered air flow rate, except under the background concentration of 18 μg/m^3. Note that the $PM_{2.5}$ concentration inside the mask at a maximum filtered air flow rate of 38.64 L/min was still higher than the $PM_{2.5}$ concentration in the HEPA filtered air. This implies significant leakage of ambient $PM_{2.5}$ into the cotton mask. The concentrations inside the cotton mask were also apparently higher than those measured in the surgical mask. Therefore, it can be concluded that the protection provided by the N95 mask was the best, while that provided by the cotton mask was the worst.

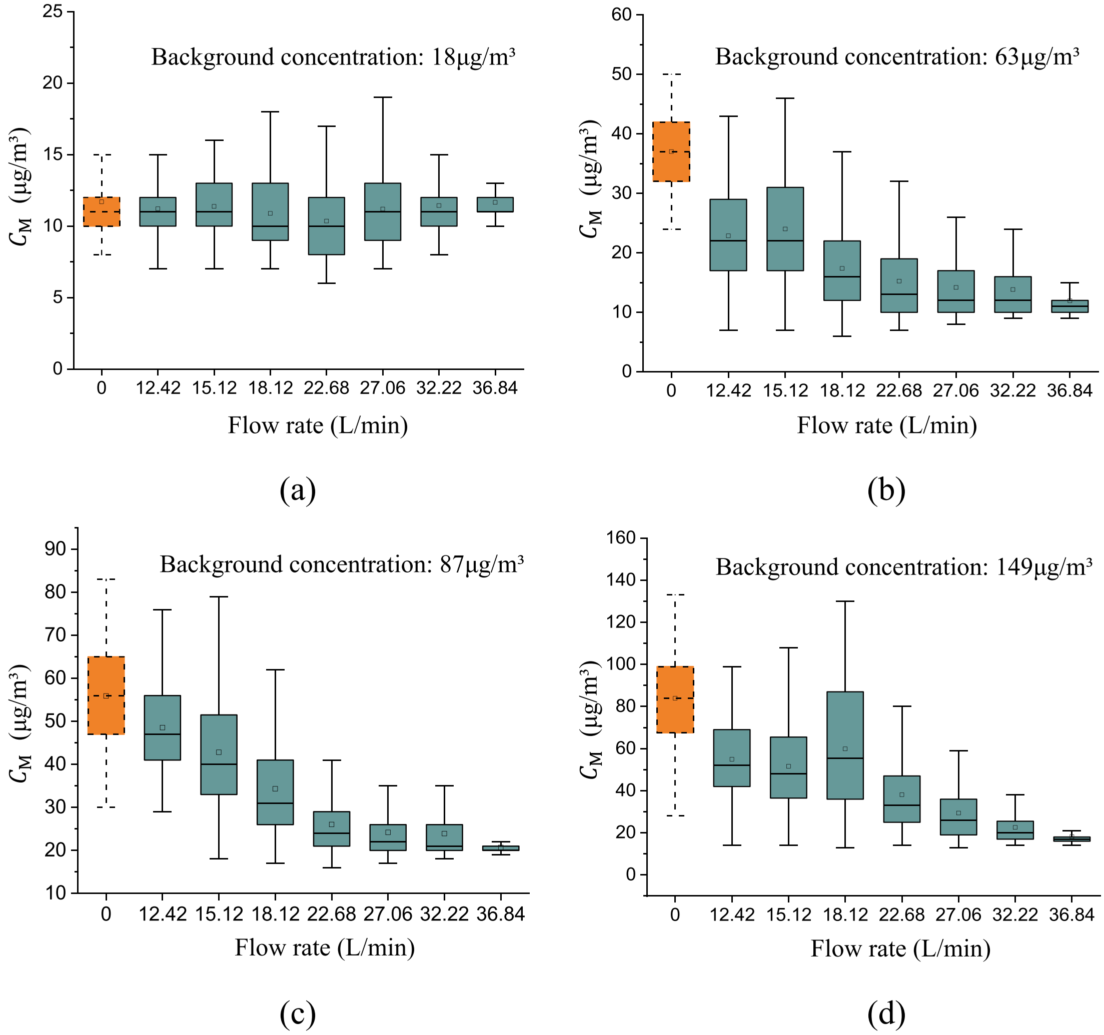

Fig. A.3. Measured $PM_{2.5}$ concentrations inside the cotton mask versus the filtered air-supply rate into the mask under different background $PM_{2.5}$ concentrations.

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